APEX Feedlot Water Quality Simulation

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Abstract. *A manure erosion equation was developed and added to the APEX model for use in estimating nutrient losses from feedlots and manure application fields. The modified APEX was validated with data from feedlots near Bushland, Texas, and Carrington, North Dakota. The model was used to investigate feedlot management options on a hypothetical feedlot with realistic data. Vegetative filter strip (VFS) characteristics including 10%, 25%, 50%, and 100% FLRs (flow length ratios, i.e., filter flow length/feedlot flow length) and slopes of 1%, 5%, and 10% were considered. Combinations of these VFS characteristics were compared on two soil types: clay loam and fine sandy loam. Management options included three stocking rates (10, 15, and 20 m^2 head^{-1}) and two clean-out intervals (90 and 180 d). Additionally, two climatic conditions (precipitation of 440 and 825 mm year^{-1}) were simulated. Results from 50-year simulations indicate that a VFS downslope of the feedlot can greatly reduce nutrient loads. All three VFS characteristics (FLR, slope, and soil) were important in controlling organic N and P losses. The best organic N and P control was obtained from a VFS with maximum FLR (100%), minimum slope (1%), and a sandy loam soil. Results were similar for soluble N and P control except that VFS slope had little effect. The simulated management options (clean-out interval and stocking rate) were also effective in controlling nutrient losses. The climatic variable (annual precipitation) gave higher nutrient losses from the feedlot and the VFS with 825 mm than with 440 mm. Nutrient control efficiencies, CEs, 100.* (1.0 − nutrient loss from VFS / nutrient loss from feedlot) were calculated for all scenarios considered. The VFSs on sandy loam soil with FLRs equal to or greater than 50% gave the highest CEs for both soluble and organic nutrients. Other factors including VFS slope, clean-out interval, and stocking rate had marginal impacts on CE. For soluble nutrients, CE is inversely related to annual precipitation. Thus, it is important to locate feedlots in areas with low precipitation and to provide a well designed VFS. The APEX model with the new manure erosion equation provides a tool for designing VFSs for controlling nutrient losses from feedlots.*

Keywords. *APEX model, Feedlot, Filter strips, Manure erosion, Nutrient runoff, Water quality.*

Traditionally, USEPA has considered dairies and other concentrated animal feeding facilities as “point” sources. The discharge standard that has been applied to feedlot facilities is known as the “zero-discharge standard” in which the release of processed wastewater or other water such as rinse (wash-off) water and natural rainfall runoff that contacts manure or other waste products is not permitted. A Notice of Data Availability (NODA) modified this zero-discharge regulation on July 23, 2002, to include the exception that storm water may be released from retention facilities such as ponds and lagoons from a 24-hour storm event that is statistically greater than that which would be expected once every 25 years (the 25-year, 24-hour rule) (Federal Register, 2002; Auvermann, 2002). The animal industry reaction to the zero-discharge regulation was to construct ponds and lagoons that would contain runoff from dairy and feeding facilities. In the NODA, USEPA proposes to develop a voluntary program intended to facilitate the use of new technologies and practices for wastewater control. A potential alternative for minimizing runoff volume and manure solids from feeding areas into ponds and lagoons is placing a vegetative filter strip (VFS) between the source and the holding facility or stream. While some existing facilities may have little flexibility in adjusting their spatial design, new ones and those that have adequate space can use the results of this study for improved design considerations. Additionally, improved management of feedlot conditions can be implemented by those who do not have space for VFS establishment.

Gilbertson et al. (1972) indicated that designs of runoff control facilities for cattle feedlots should include considerations of climate, physical and topographic characteristics, and the water pollution potential of the site. The Agricultural Waste Management Handbook (USDA-NRCS, 1992) indicates that runoff N concentration declines with increasing rainfall and with lower stocking rates in combination with a VFS or settling basins.

Magette et al. (1989) reported on the effectiveness of several characteristics of VFS in removing nutrients and sediment from runoff. Using a rainfall simulator, both total suspended solids (TSS) and total P losses were reduced substantially by plot lengths of 4.6 and 9.2 m compared with

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no VFS, but total N was reduced by the longest plot only. Losses increased when soil water content increased and more runoff events occurred. The effectiveness of VFS diminished as the ratio of vegetated area to non-vegetated area decreased. Others have reported similar impacts on losses by VFS length and ratio to the runoff area (Edwards et al., 1996; Dickey and Vanderholm, 1981; Bingham et al., 1980; Doyle et al., 1977; Dillaha et al., 1987, 1989).

The Agricultural Policy/ Environmental eXtender (APEX) model (Williams et al., 1998; Williams et al., 2000; Williams and Izaurralde, 2005a, 2005b) was developed for use in whole farm/small watershed management. A manure erosion equation was developed and added to the APEX model for use in estimating nutrient losses from feedlots and manure application fields.

The purpose here is to describe the development of the manure erosion equation, to describe other APEX components essential for simulating feedlot water quality, to validate the model with limited data, and to simulate feedlot water quality as affected by various management strategies.

APEX Model Description

APEX was constructed to evaluate various land management strategies considering sustainability, erosion (wind, sheet, and channel), economics, water supply and quality, soil quality, plant competition, weather, and pests. Management capabilities include irrigation, drainage, furrow diking, buffer strips, terraces, waterways, fertilization, manure management, lagoons, reservoirs, crop rotation and selection, pesticide application, grazing, and tillage. The model operates on a daily time step (some processes are simulated with hourly or less time steps) and is capable of simulating hundreds of years if necessary. Farms may be subdivided into fields, soil types, landscape positions, or any other desirable configuration.

The individual field simulation component of APEX is taken from the Environmental Policy Integrated Climate (EPIC) model, previously the Erosion Productivity Impact Calculator (Williams, 1995). Various components from CREAMS (Knisel, 1980) and SWRRB (Williams et al., 1985) were used in developing EPIC, and the GLEAMS (Leonard et al., 1987) pesticide component was added later. The drainage area considered by EPIC is generally a field-size area, up to 100 ha, where weather, soils, and management systems are assumed to be homogeneous.

The APEX model was developed to extend the EPIC model capabilities to whole farms and small watersheds. In addition to the EPIC functions, APEX has components for routing water, sediment, nutrients, and pesticides across complex landscapes and channel systems to the watershed outlet. APEX also has groundwater and reservoir components. A watershed can be subdivided as much as necessary to ensure that each subarea is relatively homogeneous in terms of soil, land use, management, etc. The routing mechanisms provide for evaluation of interactions between subareas involving surface runon, return flow, sediment deposition and degradation, nutrient transport, and groundwater flow. Water quality in terms of soluble and organic N and P, and pesticide losses may be estimated for each subarea and at the watershed outlet. The major uses of APEX have been in dairy manure management to maintain water quality in the Texas counties of Erath and Hopkins (Flowers et al., 1996) and in a national study to assess the effectiveness of vegetative filter strips (VFS) in controlling sediment and other pollutants (Arnold et al., 1998). APEX has also been used in several studies of watershed management evaluating conservation tillage effects on atrazine and manure nutrient losses from application fields (Wang et al., 2002; Harman et al., 2004).

The APEX model has been described in detail (Williams et al., 2000; Williams and Izaurralde, 2005a, 2005b). Only brief descriptions of the components essential for simulating feedlot water quality are presented here.

Hydrology

Surface Runoff

The runoff model simulates surface runoff volumes and peak runoff rates, given daily rainfall amounts. Two methods are provided for estimating runoff volume: a modification (Williams, 1995) of the Soil Conservation Service (SCS) curve number technique (USDA-SCS, 1972), and the Green and Ampt infiltration equation (Green and Ampt, 1911). The curve number technique was selected for use because: (1) it is reliable and has been used for many years in the U.S., (2) it is computationally efficient, (3) the required inputs are generally available, and (4) it relates runoff to soil type, land use, and management practices. The use of readily available daily rainfall data is a particularly important attribute of the curve number technique because for many locations, rainfall data with time increments of less than one day are not available. In addition, rainfall data manipulations and runoff computations are more efficient for data taken daily than at shorter intervals. One of the major criticisms of the curve number method is its failure to account for rainfall intensity. Thus, the Green and Ampt method is offered as an option. Daily rainfall is distributed exponentially with parameters generated stochastically to provide rates needed for Green and Ampt. There are two options for estimating the peak runoff rate: the modified Rational formula (Williams, 1995), and the SCS TR-55 method (USDA-SCS, 1986). A stochastic element (Williams, 1995) is included in the Rational equation to allow realistic simulation of peak runoff rates, given only daily rainfall and monthly rainfall intensity.

Evapotranspiration

The model offers five options for estimating potential evaporation: Hargreaves and Samani (1985), Penman (1948), Priestley and Taylor (1972), Penman-Monteith (Monteith, 1965), and Baier and Robertson (1965). The Penman and Penman-Monteith methods require solar radiation, air temperature, wind speed, and relative humidity as input. If wind speed, relative humidity, and solar radiation data are not available, the Hargreaves or Priestley-Taylor methods provide options that give realistic results in most cases. The Baier-Robertson method developed in Canada performs well in cold climates. The model computes evaporation from soils and plants separately, as described by Ritchie (1972). Potential soil water evaporation is estimated as a function of potential evaporation and leaf area index (LAI, area of plant leaves relative to the soil surface area) (Williams, 1995). Actual soil water evaporation is estimated by using exponential functions of soil depth and water content (Williams, 1995). Plant water evaporation is simulated as a linear function of potential evaporation and leaf area index.

EROSION

The APEX component for water-induced erosion simulates erosion caused by rainfall and runoff and by irrigation (sprinkler and furrow). To simulate rainfall/runoff erosion, APEX contains seven equations: the USLE (Wischmeier and Smith, 1978), the Onstad-Foster modification of the USLE (Onstad and Foster, 1975), the MUSLE (Williams, 1975), two variations of MUSLE (Williams, 1995), a MUSLE structure that accepts input coefficients, and RUSLE (Renard et al., 1997). Only one of the equations (user specified) interacts with other APEX components. The seven equations are similar except for their energy components. The USLE and RUSLE depend strictly upon rainfall as an indicator of erosive energy. The MUSLE and its variations use only runoff variables to simulate erosion and sediment yield. Runoff variables increase the prediction accuracy, eliminate the need for a delivery ratio (used in the USLE to estimate sediment yield), and enable the equation to give single-storm estimates of sediment yields. The USLE gives only annual estimates. The Onstad-Foster equation contains a combination of the USLE and MUSLE energy factors. The RUSLE provides improved methods for computing the crop cover factor and the slope length factor especially for steep slopes.

NUTRIENTS

Nitrogen

NO_3-N Losses by Leaching, Surface Runoff, Lateral Subsurface Flow: The amount of NO_3-N lost when water flows through a layer is estimated by considering the change in concentration (Williams, 1995). NO_3-N concentration in a soil layer decreases exponentially as a function of flow volume. The average concentration during a day is obtained by integrating the exponential function with respect to flow. Amounts of NO_3-N contained in runoff, lateral flow, and percolation are estimated as products of the volume of water and the average concentration.

Organic N Transport by Sediment: A loading function developed by McElroy et al. (1976) and modified by Williams and Hann (1978) for application to individual runoff events is used to estimate organic N loss. The loading function considers sediment yield, organic N concentration in the soil surface, and an enrichment ratio. The enrichment ratio is the concentration of organic N in the sediment divided by that in the soil. Enrichment ratios are logarithmically related to sediment concentration, as described by Menzel (1980). An individual-event enrichment to sediment concentration relationship was developed for EPIC (Williams, 1995) considering upper and lower bounds. The upper bound of the enrichment ratio is the inverse of the sediment delivery ratio (DR). Exceeding the inverse of the delivery ratio implies that more organic N leaves the watershed than is dislodged from the soil. The lower limit of the enrichment ratio is 1.0, i.e., sediment particle size distribution is the same as that of the soil. For the enrichment ratio to approach 1.0, the sediment concentration must be extremely high. Conversely, for the enrichment ratio to approach 1/DR, the sediment concentration must be low.

Denitrification: As one of the microbial processes, denitrification is a function of temperature and water content (Williams, 1995). Anaerobic conditions are required and a carbon source must be present for denitrification to occur.

Mineralization: The N mineralization model is a modification (Williams, 1995) of the PAPRAN mineralization model (Seligman and van Keulen, 1981). The model considers two sources of mineralization: the fresh organic N pool, associated with crop residue and microbial biomass, and the stable organic N pool, associated with the soil humus. Mineralization from the fresh organic N pool is a function of C:N ratio, C:P ratio, composition of crop residue, temperature, and soil water. Organic N associated with humus is divided into two pools: active and stable. The pool sizes are estimated based on the years of cultivation at the start of the simulation. The total organic N is given or can be estimated from the organic C. The active fraction of total organic N is relatively large for virgin sod and decreases as the years of cultivation increase. Below the plow layer, the active pool fraction is set at 40% of the plow layer value, based on work of Cassman and Munns (1980). Organic N flux between the active and stable pools flows at a rate of 1.e-5 d^{-1} and the original equilibrium is maintained. Only the active pool of organic N is subjected to mineralization. Humus mineralization is a function of soil water content, temperature, and bulk density. To maintain the N balance at the end of the day, the humus mineralization is subtracted from the active organic N pool, the residue mineralization is subtracted from the fresh organic N pool, 20% of the residue mineralization is added to the active ON pool, and 80% is added to the mineral N pool.

Immobilization: The daily amount of immobilization is computed by subtracting the amount of N contained in the crop residue from the amount assimilated by the microorganisms (Williams, 1995). We assume that 40% of the fresh crop residue is carbon, that the C:N of the microbial biomass and their labile products is 10, and that 0.4 of C in the residue is assimilated. Immobilization may be limited by N or P availability.

Nitrification: Nitrification, the conversion of ammonia N to NO_3-N, is estimated using a combination of the methods of Reddy et al. (1979) and Godwin et al. (1984). The approach is based on the first-order kinetic rate equation of Reddy et al. (1979). The equation combines nitrification and volatilization regulators. The nitrification regulator is a function of temperature, soil water content, and soil pH.

Volatilization: Volatilization, the loss of ammonia to the atmosphere, is estimated simultaneously with nitrification. Volatilization of surface-applied ammonia is estimated as a function of temperature and wind speed (Williams, 1995). Depth of ammonia within the soil, cation exchange capacity of the soil, and soil temperature are used in estimating below surface volatilization.

Phosphorus

Soluble P Loss in Surface Runoff: The APEX approach is based on the concept of partitioning pesticides into the solution and sediment phases, as described by Leonard and Wauchope (Knisel, 1980). Because P is mostly associated with the sediment phase, the soluble P runoff equation is a linear function of soluble P concentration in the top soil layer, runoff volume, and a linear adsorption isotherm.

P Transport by Sediment: Sediment transport of P is simulated with a loading function, as described for organic N transport. The P loading function considers sediment yield, organic P concentration in the top soil layer, and the enrichment ratio.

Mineralization: The P mineralization model developed by Jones et al. (1984) is similar in structure to the N mineralization model. Mineralization from the fresh organic P pool is estimated as the product of the mineralization rate constant and the fresh organic P content. Mineralization of organic P associated with humus is estimated for each soil layer as a function of soil water content, temperature, and bulk density.

Immobilization: The P immobilization model, also developed by Jones et al. (1984), is similar in structure to the N immobilization model. The daily amount of immobilization is computed by subtracting the amount of P contained in the crop residue from the amount assimilated by the microorganisms. We assumed that C = 0.4 of the crop residue, that 0.4 of that C is assimilated by soil microorganisms, and that the P:C ratio of soil microorganisms ranges from 0.01 to 0.02 as a function of labile P concentration.

MANURE EROSION

Manure is eroded from feeding areas and manure application fields. Depending on the amount of manure cover of the soil, the erosion varies from essentially all manure to a combination of manure and soil. Since manure is considered residue, a heavy cover in a feedlot may completely eliminate soil erosion but create the potential for severe manure erosion. Soil erosion potential is also very low in manure application fields with a good grass cover, but manure erosion can be high. Losses of organic nutrients and carbon are usually estimated using an enrichment ratio, the nutrient concentration in the soil, and the soil erosion rate, as described above. However, this approach underestimates organic nutrient and C losses because the soil erosion rates are near zero. This deficiency created the need for a manure erosion equation that provides direct estimates of organic nutrient and C losses. The equation is based on the soil erosion equation MUST (Williams, 1995):

$$\begin{aligned} YMNU &= 0.25*(Q*qp)^{0.5}*PE*SL \\ &*RSDM^{0.5}*\exp(-0.15*AGPM)) \end{aligned} \tag{1}$$

where YMNU is the manure erosion (t ha^{-1}), Q is the runoff volume (mm), qp is the peak runoff rate (mm h^{-1}), PE is the erosion control practice factor, SL is the slope length and steepness factor, RSDM is the manure on the soil surface (t ha^{-1}), and AGPM is the standing live and dead plant material. The losses of organic nutrients and C are calculated as the product of YMNU and the fractions of organic N, P, and C in the manure.

APEX ROUTING COMPONENT

Water

Since the primary purpose of APEX is to simulate long-term water, sediment, nutrient, and pesticide yields from whole farms and small watersheds, traditional flood routing methods are not used (Williams et al., 2000; Williams and Izaurralde, 2005a, 2005b). In addition, the daily time step prohibits adequate hydrograph definition for small areas (time of concentration <4 d). The average flow rate for a runoff event is estimated as a function of runoff volume, watershed area, rainfall duration, and time of concentration. The channel capacity is estimated using Manning's equation assuming a trapezoidal shape. If the daily flow rate is less than channel capacity, then flow is contained in the channel and the flow velocity is calculated using Newton's method for solving nonlinear equations. The solution involves adjusting flow depth to give the correct flow rate. Then channel flow velocity is computed by dividing rate by cross-sectional area. If the channel capacity is exceeded, the excess flow occurs in the floodplain. Flow depth is calculated using Manning's equation. Flow velocity is computed by dividing rate by area. Travel time through the reach floodplain is length divided by velocity. The inflow volume is reduced by floodplain infiltration. Although the geometry of a VFS is quite different from that of most natural routing reaches, the APEX routing component is directly applicable. The VFS is a very short routing reach with a wide floodplain and no channel capacity.

Sediment

Sediment is routed through the channel and floodplain separately (Williams et al., 2000; Williams and Izaurralde, 2005a, 2005b). The sediment routing equation is a variation of Bagnold's sediment transport equation (Bagnold, 1977). The new equation estimates the transport concentration capacity as a function of velocity:

$$CYU = CY1*VCH^{1..5} \tag{2}$$

where CYU is the potential sediment concentration (t m^{-3}) for flow velocity VCH (m s^{-1}), and CY1 is the potential sediment concentration for velocity equal to 1.0 m s^{-1}. The potential change in sediment yield through a routing reach is calculated as the difference between inflow and potential concentration:

$$\begin{aligned} YU &= 10.*(QO*CYU-QI*CIN) \\ &*(1.0-\exp(-3.0*TRT*PSZM)) \end{aligned} \tag{3}$$

where YU is the potential change in sediment yield (t ha^{-1}), QI is the reach inflow volume (mm), QO is the reach outflow volume (mm), CIN is the inflow sediment concentration (t m^{-3}), TRT is the travel time through the reach (h), and PSZM is the mean sediment particle size (μm). If YU is negative, deposition occurs in the reach:

$$DEP = -YU \tag{4}$$

where DEP is sediment deposition in the reach (t ha^{-1}). If YU is positive, channel degradation is calculated with the equation:

$$DEG = YU*EK*CVF \tag{5}$$

where DEG is the channel degradation (t ha^{-1}), EK is the USLE soil erodibility factor, and CVF is the USLE plant cover factor. As sediment is routed through a reach, the particle size distribution also changes. APEX represents sand, silt, and clay with particle sizes of 200, 10, and 2 μm, respectively. Sediment particles are deposited as an exponential function of the square root of particle size (Williams and Hann, 1978).

Nutrients

The organic forms of N and P are transported by sediment and are routed using an enrichment ratio approach (Williams et al., 2000; Williams and Izaurralde, 2005a, 2005b). The enrichment ratio is estimated as the ratio of the mean sediment particle size distribution of the outflow divided by that of the inflow. Mineral forms of N and P are considered conservative and thus maintain a constant concentration as they flow through a reach. Mineral nutrient losses occur only if flow is lost within the reach.

Manure Management

Manure may be applied as solid or liquid. Confined feeding areas may contain a lagoon to catch runoff from the feeding area plus wash water that is used in the barn. The lagoon is designed automatically by the model considering normal and maximum volumes. The storage between normal and maximum is set to contain the runoff from a design storm plus 30 days of wash water. The design storm is equal to twice the largest value of average monthly rainfall, and runoff is estimated assuming a NRCS runoff curve number of 90. The normal volume is a user-supplied fraction of the maximum volume. Effluent from the lagoon is applied automatically to a field designated for liquid manure application. The liquid manure application rules are: (1) pumping begins when the lagoon volume exceeds 0.75 of the difference between maximum and normal lagoon volumes, (2) the pumping rate is set to reduce the lagoon volume from maximum to normal in a user-supplied number of days, (3) pumping can also be triggered by a user-supplied date, usually before winter or a high rainfall season. Solid manure is scraped from the feeding area automatically at a user input interval in days and stockpiled for automatic application to designated fields. An owner may have any number of solid manure application fields. When an application is triggered (the stockpile is adequate to supply the specified rate), manure is applied to the field with the lowest soluble P concentration in the top 50 mm of soil. A variety of livestock including cattle, swine, and poultry may be considered because manure production (kg head^{-1} d^{-1}) and its ingredients (mineral and organic N and P) are inputs. APEX simulates runoff, soil erosion, and manure erosion. Routing mechanisms simulate soluble nutrient transport with water, organic nutrient transport by sediment, and manure transport by water.

Model Validation

Data from feedlots near Bushland, Texas, and Carrington, North Dakota, were used in model validation. Clark et al. (1975) reported results of runoff measurements taken during 1971-1973 from feedlots in the Texas High Plains. They determined that 10 mm of rainfall was required to induce runoff from feedlots at Bushland, Texas, and that the runoff was linearly related to rainfall. They also reported highly variable nutrient losses in runoff with average values of 1083 g m^{-3} N and 205 g m^{-3} P. These data were used to validate the APEX runoff, nutrient, and manure erosion components. Measured daily rainfall and maximum and minimum temperature were input. The 4 ha feedlot had a 2% slope and a stocking rate of 13.33 m^2 head^{-1}. The simulated results using APEX compared closely with the 1971-1973 measured data. Simulated and measured average values of runoff were 58 and 53 mm year^{-1}, soluble N loss concentrations were 1162 and 1083 g m^{-3}, soluble P loss concentrations were 241 and 205 g m^{-3}, and suspended solids concentrations were 15934 and 15000 g m^{-3}, respectively. Guidelines categorized by rainfall amounts have been suggested by USDA-NRCS for N losses from a beef cattle feedlot (USDA-NRCS, 1992). The guideline is 1590 g m^{-3} N loss in runoff for feedlots located in semi-arid regions having less than 635 mm year^{-1} rainfall with a stocking rate of 16.21 m^2 head^{-1}. The simulated and measured losses are similar to the guidelines, considering that the average rainfall during the study was 429 mm year^{-1} with a stocking rate of 13.33 m^2 head^{-1}.

Kizil et al. (2006) reported results of runoff and nutrient measurements taken during 2001-2002 from a small bison feedlot near Carrington, North Dakota. The 462 m^2 feedlot had a 4% slope and a stocking rate of 46.2 m^2 head^{-1} of bison. Kizil et al. (2006) applied the Soil Conservation Service (SCS) curve number equation (USDA-SCS, 1972) to the 13 runoff-producing storms that occurred during 2001-2002. They reported that a curve number of 93 produced the highest correlation (0.85) between observed and simulated runoff. Although the soil is a Heimdal-Emrick, which is in hydrologic soil group B (permeable), the fly-ash stabilized surface produced high runoff (93 curve number). APEX produced similar results since the curve number runoff option was used. However, we found that a 95 curve number gave slightly better results. The mean observed runoff was 10.05 mm. Simulation results using curve numbers 93 and 95 are given in table 1.

Kizil et al. (2006) reported nutrient concentrations in the bison manure and in the runoff from the feedlot. The manure nutrient concentrations, feedlot slope, stocking rate, and the daily observed weather (maximum and minimum temperature, solar radiation, precipitation, dew point temperature, and wind speed) were important APEX inputs. The daily manure production was assumed to be 7.0 kg head^{-1} d^{-1} and there was no pen clean-out during 2001-2002. The measured and simulated nutrient concentrations are given in table 2.

VFS Characteristics and Management Options

This investigation analyzed the impacts of establishing perennial grasses as a VFS of varying dimensions and topographic characteristics between the feeding area and lagoon or stream. Advantages of using perennial grasses in VFS compared with annual crops or grasses include: (1) perennial crops like grass minimize soil erosion since no cultivation is required after establishment, (2) grass management practices can include or exclude removal of the surface biomass depending on optimum grass-life longevity and production characteristics, and (3) grass maintenance expenses are small after establishment, which is important economically, since there may be a potential loss of revenue if the dedicated area was originally in cash crop production.

Table 1. Simulation results using curve numbers 93 and 95 for a feedlot in Carrington, North Dakota.

Curve Number	Mean Runoff (mm)	Standard Error (mm)	Explained Variance	R^2
93	7.82	4.05	0.52	0.72
95	10.02	3.60	0.62	0.73

Table 2. Measured and simulated nutrient concentrations for a feedlot in Carrington, North Dakota.

	Organic N (ppm)	Mineral N (ppm)	Total P (ppm)
Manure	4925	348	4377
Runoff, observed	95	58	50
Runoff, simulated	100	67	51

Simulations were based on a hypothetical feedlot 200 m long by 50 m wide with a slope of 2% along the length and 0% across the width. The VFS was placed immediately downslope from the feedlot along the 50 m width. Flow length across the filter was varied to estimate the effect of FLR on controlling nutrient losses and the filter efficiency. Four filter flow lengths of 20, 50, 100, and 200 m were selected to give FLRs of 10%, 25%, 50%, and 100%. Additionally, three filter flow length slopes (1%, 5%, and 10%) and two soil types of 15.5% sand (clay loam) and 52.2% sand (fine sandy loam) were simulated.

Management options included varying stocking rates (10, 15, and 20 m^2 $head^{-1}$) and clean-out intervals (90 and 180 d). These clean-out intervals represent the majority of cattle feedlots in the southern Great Plains (Harman, 2004). Daily manure production was assumed to be 4.5 kg $head^{-1}$ (90% occupancy) composed of 2.38% mineral N (99% in NH_3-N form), 0.8% mineral P, 1.04% organic N, and 0.4% organic P. Two locations, Dimmitt, Texas (semi-arid) and St. Louis, Missouri (humid), were selected and the APEX weather generator was used to simulate daily maximum and minimum temperature, solar radiation, precipitation, relative humidity, and wind speed for 50-year durations. The total simulations included 144 combinations of VFS characteristics and feedlot management options for each of two climatic conditions.

SIMULATION RESULTS

Since all combinations of the VFS characteristics, management options, and rainfall conditions resulted in 14400 simulations, too many to include in this article, only the long-term (50-year) average nutrient losses are illustrated and discussed. This consolidation reduces the number of comparisons to 288. Furthermore, only two stocking rates, low (20 m^2 $head^{-1}$) and typical (15 m^2 $head^{-1}$), are illustrated due to the limitations of graphical representations. Higher stocking rates tend to increase nutrient losses because manure production is greater. Additionally, results from one rainfall regime, characteristic of the southern Great Plains (440 mm $year^{-1}$), are illustrated. Results from a high rainfall (825 mm $year^{-1}$) regime are discussed.

Figures 1 through 4 compare soluble and organic N and P losses in runoff and suspended solids from the feedlot and the VFS. Feedlot losses are illustrated in two sets (one set for each stocking rate) of four bars labeled “Feedlot, 2%.” While the feedlot is assumed to have almost an impermeable surface, nutrient losses from the VFS were compared for two soil types (sandy loam and clay loam). Comparisons can be made for the two soil types by viewing each pair of bars, i.e., in figures 1 through 4, the first pair of bars labeled “sandy loam 180-d” and “clay loam 180-d” (see legend). The effects of clean-out interval for each soil type can be compared by viewing alternate bars of each pair, i.e., the first bar (sandy loam 180-d) vs. the third bar (sandy loam 90-d) illustrates the effects of clean-out interval with a sandy loam topsoil for the VFS.

SOLUBLE N AND P LOSSES

Figure 1 illustrates simulated 50-year average soluble N losses from the feedlot compared with the VFS. Clearly, reducing the interval between clean-out operations decreased the losses of soluble N in runoff from the feedlot and the VFS. A similar relationship between clean-out interval and soluble N loss was established in the high rainfall feedlot. This information will be useful in establishing feedlot clean-out frequency guidelines not currently contained in NRCS handbooks. Losses from the feedlot were also reduced as the stocking rate decreased.

When a VFS was utilized downslope of the feedlot, soluble N losses were reduced below those of the feedlot in all scenarios. Of special note was the increased effectiveness in reducing soluble N losses when the VFS topsoil was sandy

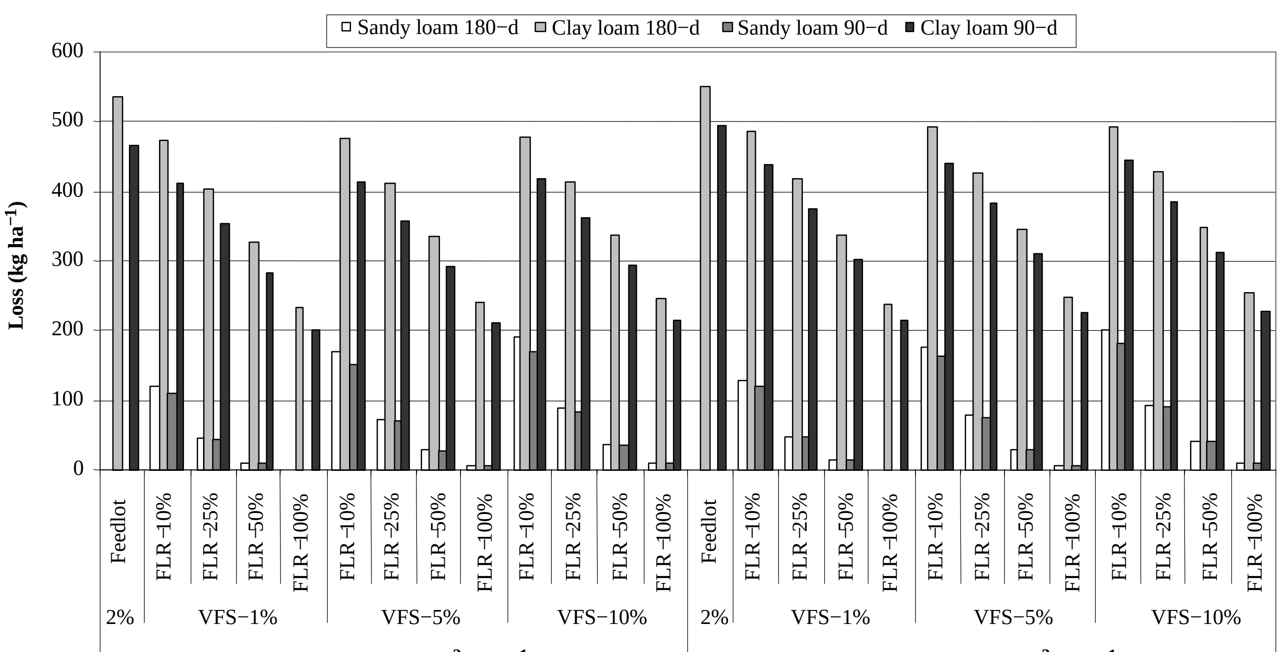

Figure 1. Simulated loss of soluble N: Feedlot vs. filter strip, 437 mm $year^{-1}$.

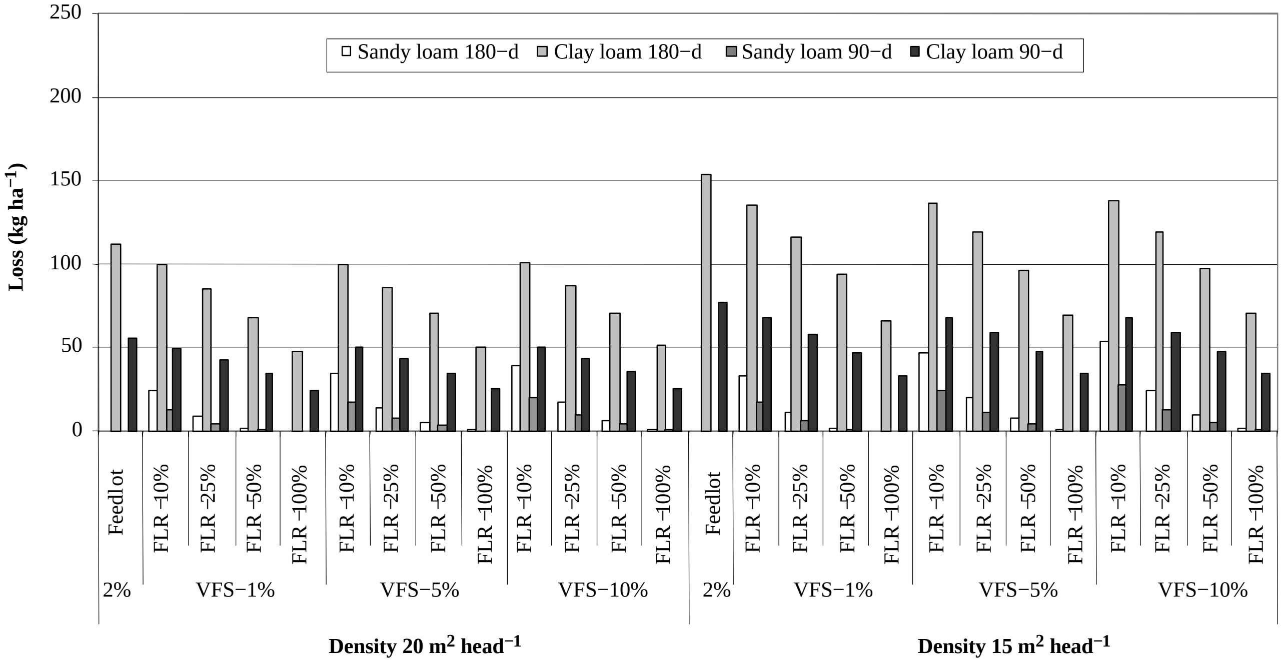

Figure 2. Simulated loss of soluble P: Feedlot vs. filter strip, 437 mm year^{-1}.

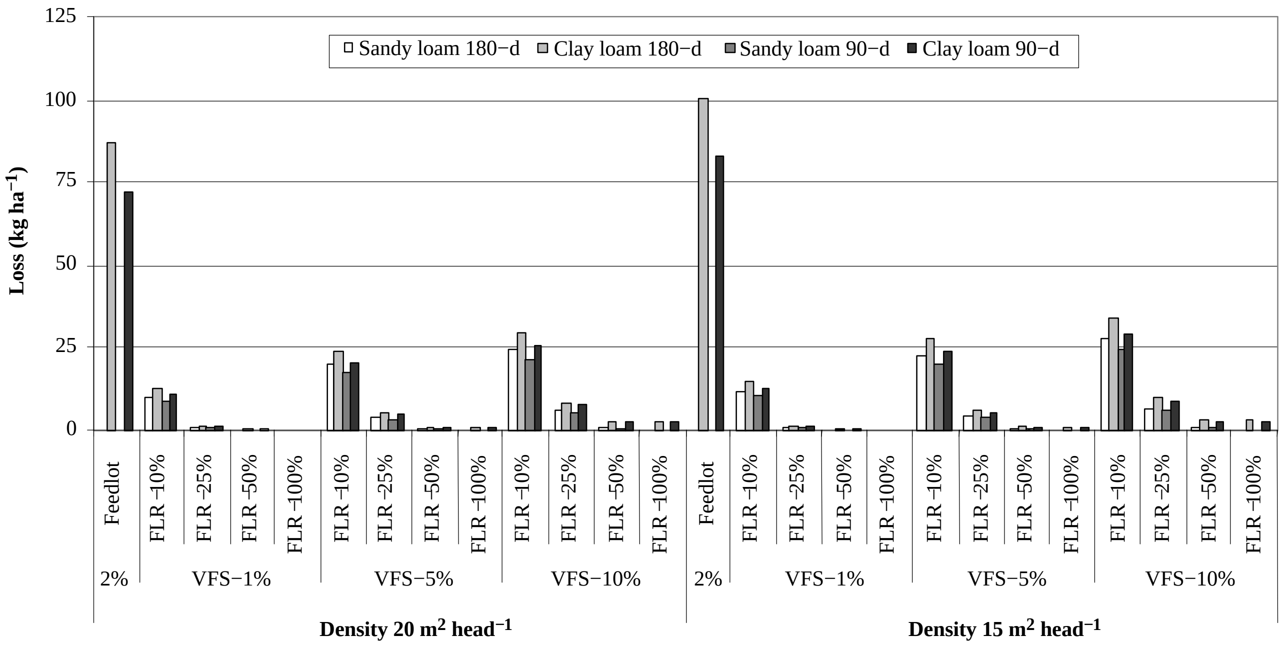

Figure 3. Simulated loss of organic N: Feedlot vs. filter strip, 437 mm year^{-1}.

loam compared with clay loam. Additionally, as FLR increased, soluble N losses decreased sharply. Although less effective, reducing the stocking rate and clean-out interval also reduced soluble N losses. Reducing the VFS slope had little impact on controlling soluble N losses. High rainfall increased VFS soluble N losses similar to the increase for a feedlot (not illustrated).

Figure 2, like figure 1, illustrates a substantial decrease in soluble P losses from the feedlot with a reduced clean-out interval. In addition, in agreement with the soluble N losses noted above, as the stocking rate increased, soluble P losses increased and this trend continued with a higher 10 m^2 head^{-1} stocking rate (not illustrated). Soluble P losses were less for the VFS with sandy loam than with clay loam. Similarly, when the stocking rate decreased or FLR increased or clean-out interval decreased, soluble P losses were reduced. The VFS slope had little effect on soluble P losses. High rainfall increased soluble P losses for all VFS scenarios.

ORGANIC N AND P LOSSES

Figures 3 and 4 illustrate large organic N and P losses leaving the feedlot compared with relatively small losses leaving the VFS with either soil type. Reducing both clean-out interval and stocking rate were effective in lowering organic N and P losses from the feedlot. The VFS with a 1% slope and a 10% FLR reduced organic nutrient

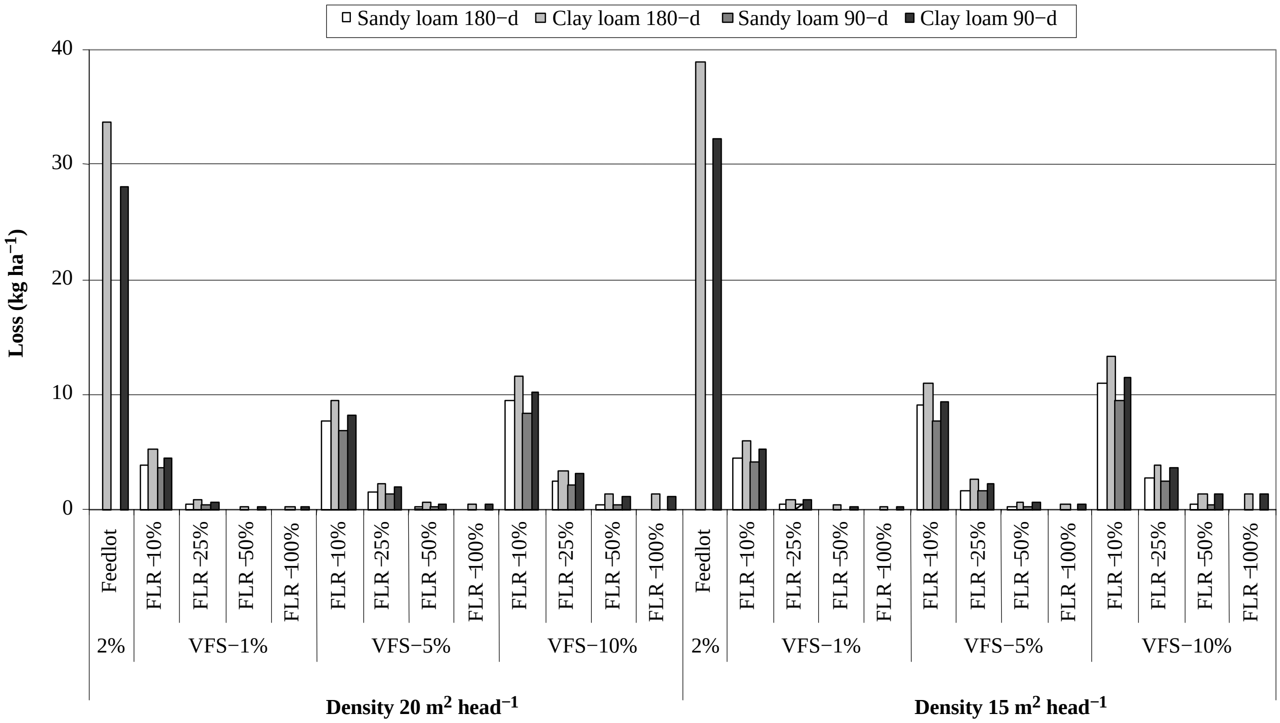

Figure 4. Simulated loss of organic P: Feedlot vs. filter strip, 437 mm year^{-1}.

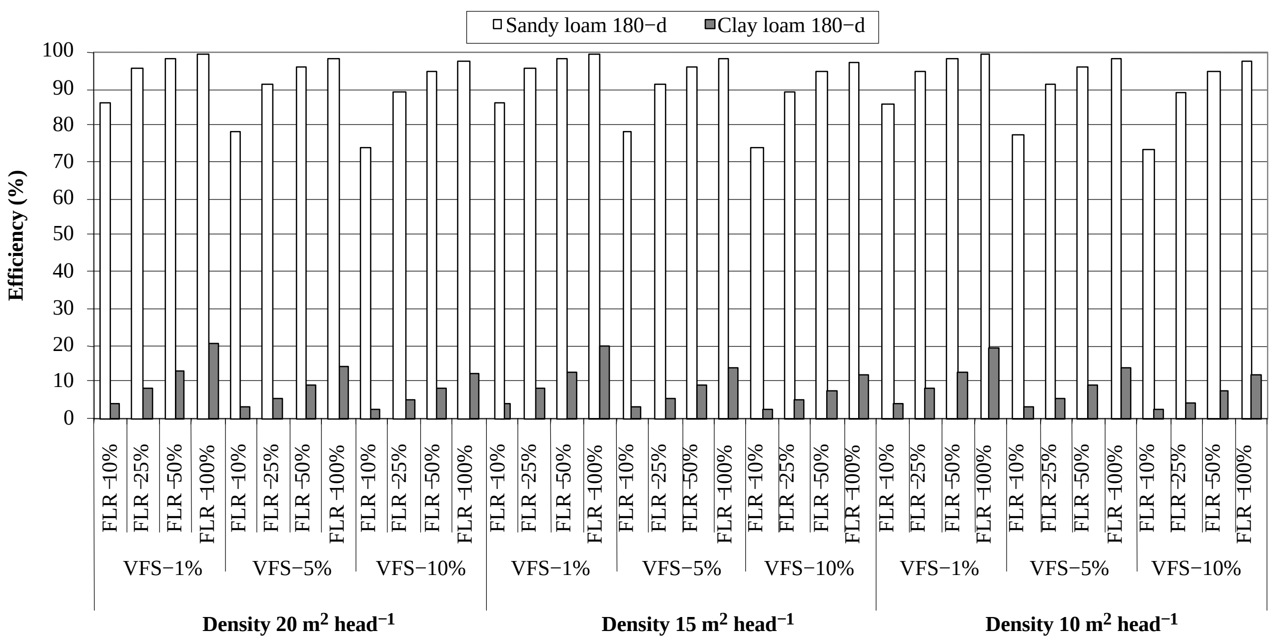

Figure 5. Efficiency of controlling soluble N losses with a filter strip, 437 mm year^{-1}.

losses by 85% to 88% depending on soil type. A 99% reduction was attained with a 1% slope and 100% FLR VFS. The VFS with a 10% slope and a 10% FLR reduced organic nutrient losses by 70% with a clay loam soil and by 65% with a sandy loam soil. Additionally, reducing the stocking rate was effective in lowering organic nutrient losses, but reducing clean-out interval was only marginally effective. High rainfall increased organic feedlot losses, as in the case for soluble nutrient losses (not illustrated). However, as FLR increased to 100%, losses were similar for both high and low rainfall scenarios.

Efficiency of Controlling Nutrient Losses

The VFS control efficiency (CE) 100.*(1.0 − nutrients leaving the VFS / nutrients leaving the feedlot) is useful in developing water quality design criteria. The CE is also useful in identifying soluble and organic nutrients that have a high potential for control. CEs were calculated for each VFS and feedlot management scenario based on 50-year simulations. Only the results from the 180-day clean-out interval and 437 mm rainfall scenarios are illustrated. Generally, decreasing the clean-out interval did not increase

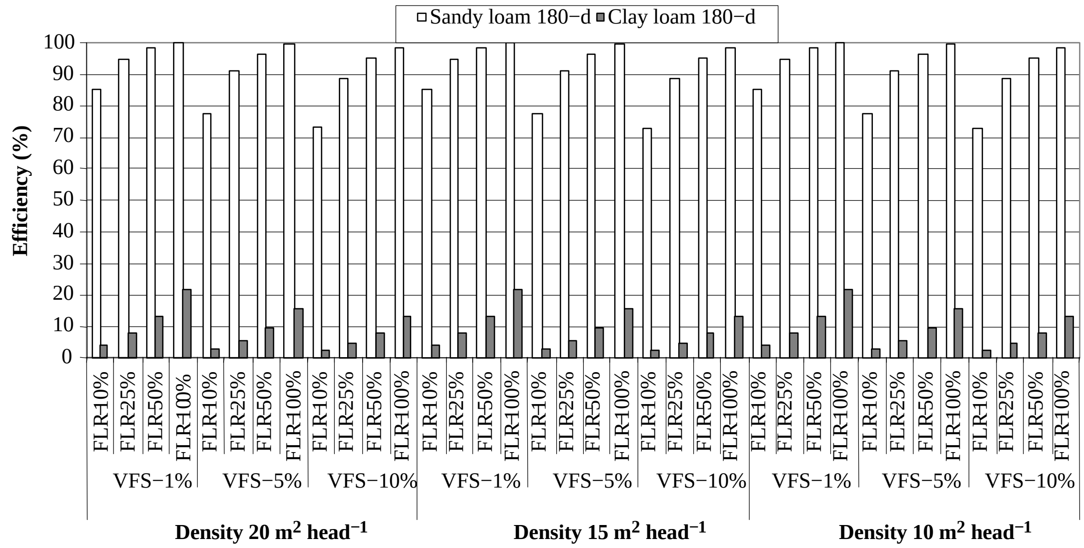

Figure 6. Efficiency of controlling soluble P losses with a filter strip, 437 mm year^{-1}.

Table 3. Effects of high rainfall on CE: percent change in CE from 437 mm year^{-1} for soluble N.

Stocking Rate	Slope (%)	FLR (%)	Sandy Loam 180-d (%)	Clay Loam 180-d (%)	Sandy Loam 90-d (%)	Clay Loam 90-d (%)
20 m^2 head^{-1}	1	10	−4	−1	−3	−2
		25	−1	−2	0	−3
		50	0	−3	0	−4
		100	0	−5	0	−4
	5	10	−6	−1	−5	−1
		25	−3	−2	−1	−2
		50	0	−2	1	−3
		100	0	−3	0	−3
	10	10	−7	−1	−5	−1
		25	−3	−1	−1	−2
		50	0	−2	1	−2
		100	1	−3	1	−2
15 m^2 head^{-1}	1	10	−6	−1	−4	−2
		25	−1	−2	−1	−3
		50	0	−3	0	−4
		100	0	−5	0	−5
	5	10	−7	−1	−6	−1
		25	−3	−2	−2	−2
		50	−1	−2	0	−3
		100	0	−3	0	−4
	10	10	−8	−1	−6	−1
		25	−4	−1	−3	−2
		50	−1	−2	0	−3
		100	1	−3	1	−3
10 m^2 head^{-1}	1	10	−6	−1	−5	−1
		25	−2	−3	−1	−3
		50	−1	−3	−1	−4
		100	0	−5	0	−5
	5	10	−8	−1	−7	−1
		25	−4	−2	−3	−2
		50	−1	−3	−1	−3
		100	0	−3	0	−4
	10	10	−8	−1	−7	−1
		25	−5	−2	−4	−2
		50	−2	−2	−1	−2
		100	0	−3	1	−3

Table 4. Effects of high rainfall on CE: percent change in CE from 437 mm year^{-1} for soluble P.

Stocking Rate	Slope (%)	FLR (%)	Sandy Loam 180-d (%)	Clay Loam 180-d (%)	Sandy Loam 90-d (%)	Clay Loam 90-d (%)
20 m^2 head^{-1}	1	10	−7	−1	−7	−1
		25	−2	−3	−3	−3
		50	−1	−4	−1	−5
		100	−1	−8	−1	−8
	5	10	−9	−1	−9	−1
		25	−5	−2	−5	−2
		50	−1	−3	−2	−4
		100	−1	−6	−1	−6
	10	10	−9	−1	−9	−1
		25	−6	−2	−6	−2
		50	−2	−3	−3	−3
		100	−1	−5	−1	−5
15 m^2 head^{-1}	1	10	−7	−1	−7	−1
		25	−2	−3	−3	−3
		50	−1	−4	−1	−5
		100	−1	−8	−1	−8
	5	10	−9	−1	−9	−1
		25	−5	−2	−5	−2
		50	−1	−3	−2	−4
		100	−1	−5	−1	−6
	10	10	−9	−1	−9	−1
		25	−6	−2	−6	−2
		50	−2	−3	−3	−3
		100	−1	−5	−1	−5
10 m^2 head^{-1}	1	10	−7	−1	−7	−1
		25	−2	−3	−2	−3
		50	−1	−4	−1	−5
		100	−1	−8	−1	−8
	5	10	−9	−1	−9	−1
		25	−5	−2	−5	−2
		50	−1	−3	−2	−3
		100	−1	−5	−1	−6
	10	10	−9	−1	−9	−1
		25	−6	−2	−5	−2
		50	−2	−3	−2	−3
		100	−1	−5	−1	−5

Table 5. Effects of high rainfall on CE: percent change in CE from 437 mm $year^{-1}$ for organic N.

Stocking Rate	Slope (%)	FLR (%)	Sandy Loam 180-d (%)	Clay Loam 180-d (%)	Sandy Loam 90-d (%)	Clay Loam 90-d (%)
20 m^2 $head^{-1}$	1	10	−1	2	−1	2
		25	0	0	0	0
		50	0	0	0	0
		100	0	0	0	0
	5	10	−1	2	0	3
		25	−1	1	0	1
		50	0	0	0	1
		100	0	1	0	1
	10	10	−2	3	−1	3
		25	0	1	0	2
		50	0	1	0	2
		100	0	3	0	4
15 m^2 $head^{-1}$	1	10	−1	2	−1	2
		25	0	0	0	0
		50	0	0	0	0
		100	0	0	0	0
	5	10	−1	3	0	3
		25	−1	1	0	1
		50	0	0	0	1
		100	0	1	0	1
	10	10	−1	3	−1	3
		25	0	1	0	2
		50	0	1	0	1
		100	0	3	0	3
10 m^2 $head^{-1}$	1	10	−1	2	−1	2
		25	0	0	0	0
		50	0	0	0	0
		100	0	0	0	0
	5	10	−1	3	0	3
		25	−1	1	0	1
		50	0	1	0	1
		100	0	1	0	1
	10	10	−1	3	−1	3
		25	0	2	0	2
		50	0	2	0	2
		100	0	3	0	3

Table 6. Effects of high rainfall on CE: percent change in CE from 437 mm $year^{-1}$ for organic P.

Stocking Rate	Slope (%)	FLR (%)	Sandy Loam 180-d (%)	Clay Loam 180-d (%)	Sandy Loam 90-d (%)	Clay Loam 90-d (%)
20 m^2 $head^{-1}$	1	10	−1	2	−1	2
		25	0	0	0	0
		50	0	0	0	0
		100	0	0	0	0
	5	10	−1	2	0	3
		25	−1	1	−1	1
		50	0	1	0	1
		100	0	1	0	1
	10	10	−2	3	−1	3
		25	−1	1	0	2
		50	0	1	0	2
		100	0	3	0	4
15 m^2 $head^{-1}$	1	10	−1	2	−1	2
		25	0	0	0	1
		50	0	0	0	0
		100	0	0	0	0
	5	10	−1	3	0	3
		25	−1	1	−1	1
		50	0	1	0	1
		100	0	1	0	1
	10	10	−2	3	−1	3
		25	−1	2	0	2
		50	0	1	0	2
		100	0	3	0	4
10 m^2 $head^{-1}$	1	10	−1	2	−1	2
		25	0	1	0	1
		50	0	1	0	0
		100	0	0	0	0
	5	10	−1	3	0	3
		25	−1	2	0	1
		50	0	1	0	1
		100	0	1	0	1
	10	10	−1	4	−1	4
		25	−1	2	0	2
		50	0	2	0	2
		100	0	3	0	4

the CE of either soluble or organic nutrient losses. However, the CEs were considerably higher for the low rainfall scenarios.

Controlling Soluble N and P Losses

Figures 5 and 6 compare the CEs of controlling soluble N and P losses with alternative VFS characteristics and management options. The CE of N and P losses were very similar for each scenario. Most importantly, increases in CE for both soluble nutrients occurred when the VFS was a sandy loam soil and by increasing FLR from 10% to 100%. Having a sandy loam soil in lieu of a clay loam increased CE in some cases nearly 85% with a FLR of 10%. In addition, depending on slope, increasing FLR from 10% to 100% resulted in a 10% to 15% increase in CE for the clay loam soil and 12% to nearly 25% for the sandy loam. Reducing VFS slope had the most beneficial impact on CE with low FLRs of 10% and 25%. Stocking rate had little positive effect on CE. The effect of increasing rainfall on CE can be seen in tables 3 through 6. Generally, CE was reduced with an increase in rainfall from 437 to 825 mm $year^{-1}$.

Controlling Organic N And P Losses

CEs of over 90% were attained for organic N and P, as shown in figures 7 and 8. The CEs were similar across scenarios for each nutrient. Increasing the FLR from 10% to 100% increased CEs. Reducing VFS slope on a sandy loam soil had a positive impact on the CE at low FLR levels. Reducing the stocking rate was only marginally effective in increasing CE. Most scenarios exceeded 90% CE in controlling organic losses, with the exception of 10% FLR with slopes of 5% and 10%. Two items are noteworthy in this respect:

- The CE for organic N and P losses usually exceeded 90% when the FLR equaled or exceeded 25%.
- Over 95% control of organic N and P loss occurred when FLR exceeded 50% combined with a slope of 5% or less.

Tables 3 through 6 shows only marginal effects on the CE of organic nutrients for the high rainfall scenarios. Impacts in this case differed by soil type: high rainfall with sandy loam resulted in CE losses ranging from 0.0% to −2.0% compared with gains in CE of 0.0% to 4% with a clay loam soil.

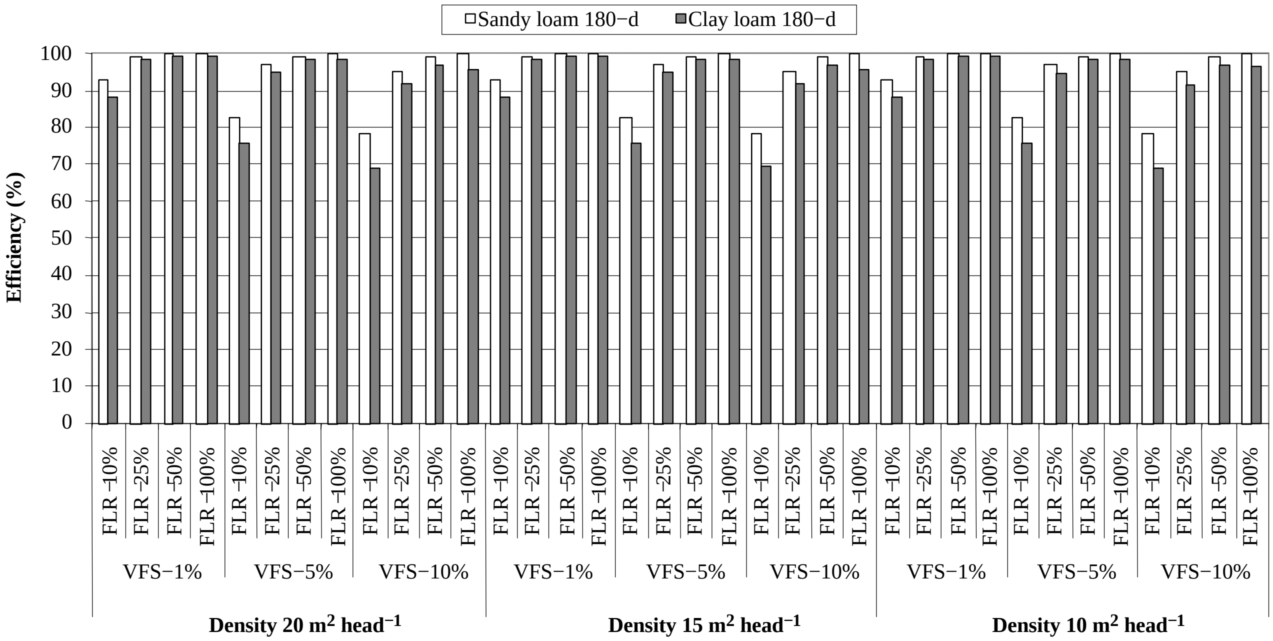

Figure 7. Efficiency of controlling organic N losses with a filter strip, 437 mm year^{-1}.

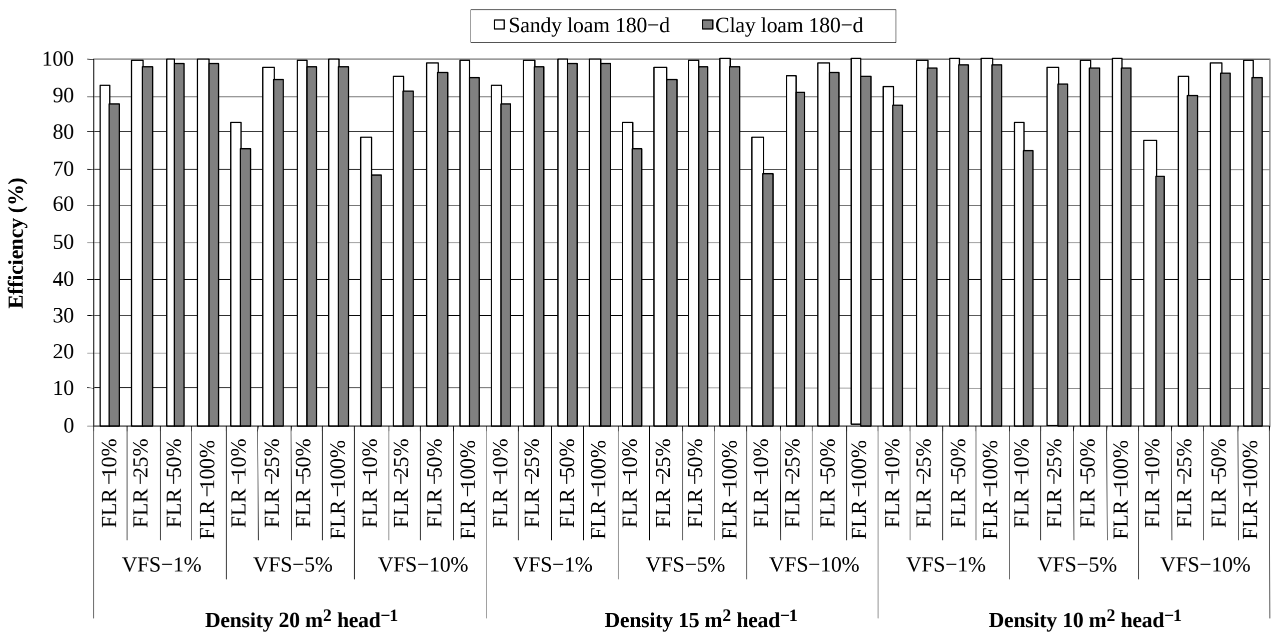

Figure 8. Efficiency of controlling organic P losses with a filter strip, 437 mm year^{-1}.

Implications and Conclusions

A new manure erosion equation was developed and added to APEX for application to water quality problems involving feedlots and manure application fields. The APEX model was used to simulate runoff, manure erosion, and N and P losses from feedlots. The model was validated using data from feedlots near Bushland, Texas, and Carrington, North Dakota. Alternative feedlot management strategies, VFS dimensions, slopes, soil textures, and annual precipitation were considered in performing 288 APEX simulations of 50-year duration each on a hypothetical feedlot using realistic data. The management strategies considered were: (1) varying feedlot stocking rates from 10 to 20 m^2 head^{-1}, and (2) using feedlot clean-out intervals of 90 and 180 d. The APEX simulations indicated that both N and P losses from feedlots are lowered by reducing both the clean-out interval and the stocking rate. These feedlot management options were more effective in areas with 825 mm year^{-1} precipitation than those with 440 mm year^{-1}. A VFS located downslope of the feedlot was effective in reducing both soluble and organic nutrient losses. The VFS is more effective if the soil is sandy loam rather than clay loam and if the FLR is maximized and the slope is minimized. However, the VFS slope variation had little effect on nutrient discharge. Feedlot managers can also reduce the clean-out interval and stocking rate to reduce nutrient losses. Reducing the clean-out interval was more important in high rainfall areas than low rainfall areas. Locating feedlots in low rainfall areas effectively reduced both soluble and organic nutrient losses from the feedlot and the VFS.

Analyses of CE determined that having a sandy loam soil for the VFS and increasing FLR to 50% or higher were the most important elements for both soluble and organic nutrient losses. Other factors, including VFS slope, clean-out interval, and stocking rate, had varied and usually marginal impacts on CE. Increasing the annual rainfall reduced the CE for soluble nutrients, but in the case of organic losses, impacts were marginal and mixed depending on soil type. Recommendations based on these simulation results are: (1) locate feedlots in relatively dry climatic areas, (2) place a well designed VFS downslope from the feedlot, and (3) lower stocking rates or clean-out intervals.

ACKNOWLEDGEMENTS

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ABBREVIATIONS

APEX	= Agricultural Policy Environmental eXtender model
CE	= VFS nutrient loss control efficiency
CREAMS	= Chemicals, Runoff, and Erosion from Agricultural Management Systems model
DR	= delivery ratio
EPIC	= Environmental Policy Integrated Climate model
FLR	= flow length ratios (filter flow length/feedlot flow length)
GLEAMS	= Groundwater Loading Effects of Agricultural Management Systems model
LAI	= leaf area index, area of plant leaves relative to the soil surface
MUSLE	= Modified Universal Soil Loss Equation
MUST	= Modified Universal Soil Loss Equation theoretically developed
NODA	= Notice of Data Availability
RUSLE	= Revised Universal Soil Loss Equation
SCS	= Soil Conservation Service
SWRRB	= Soil and Water Resources in Rural Basins model
TSS	= total suspended solids
USLE	= Universal Soil Loss Equation
VFS	= vegetative filter strip